Gravitational lensing of the farthest known supernova SN1997ff

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We investigate the effects of gravitational lensing due to intervening galaxies on the recently discovered Type Ia supernova at $z \sim 1.7$, SN1997ff, in the Hubble Deep Field North. We find that it is possible to obtain a wide range of magnifications by varying the mass and/or the velocity dispersion normalization of the lensing galaxies. In order to be able to use SN1997ff to constrain the redshift-distance relation, very detailed modeling of the galaxies to control the systematic effects from lensing is necessary. Thus we argue, that based on our current limited knowledge of the lensing galaxies, it is difficult to use SN1997ff to constrain the values of $\Omega_{\rm M}$ and Ω_Λ, or even to place severe limits on grey dust obscuration or luminosity evolution of Type Ia supernovae.

I. INTRODUCTION

A major goal of cosmology is to determine the values of various cosmological parameters such as the energy density in pressure-less matter, $\Omega_{\rm M}$, and the energy density in some energy component with negative pressure, e.g., the cosmological constant Ω_Λ. It has been long recognized that a possible method to accomplish this goal is to constrain the redshift-distance relation through the study of Type Ia supernovae (SNe). Since the redshift-distance relation is more sensitive to different values of the cosmological parameters at high redshifts, the recently discovered SN at $z \sim 1.7$ [1] might prove to be invaluable in this respect.

However, different systematic effects such as obscuration by grey dust, luminosity evolution of Type Ia SNe and gravitational lensing are also possibly more severe at high redshifts. In Ref. [2,3], the systematic effects of gravitational lensing on a large sample of SNe have been investigated.

In this paper, we investigate the effects of gravitational lensing due to galaxies lying close to the line-of-sight to SN1997ff, generalizing the work of Lewis and Ibata [4] and Riess et al. [1] by investigating the combined effects from a larger number of galaxies and estimating the masses and velocity dispersion of the lensing galaxies from the measured luminosities.

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Riess et al. [1] argued that the observed brightness of SN1997ff suggests that there cannot be a sizeable luminosity evolution for Type Ia's nor significant extinction by dust. Our work shows that the possible lensing magnification effects are large enough that the data is also consistent with an intrinsically dimmer supernova, or with significant dust density along the line-of-sight.

II. METHOD

From the Hubble Deep Field North (HDF-N; [5]), we obtain the relative positions and redshifts of galaxies lying in the proximity of the line-of-sight to SN1997ff. When spectroscopic redshifts are available we will use these, otherwise we use the photometric redshifts. We will assume that the errors due to uncertainties in the positions and redshifts are negligible in comparison to the errors due to the uncertainties in the modeling of the lensing galaxies.

In Fig. 1, we plot the relative positions of the galaxies lying closer than 10 arcseconds to the line-of-sight to SN1997ff and its host galaxy No. 531.

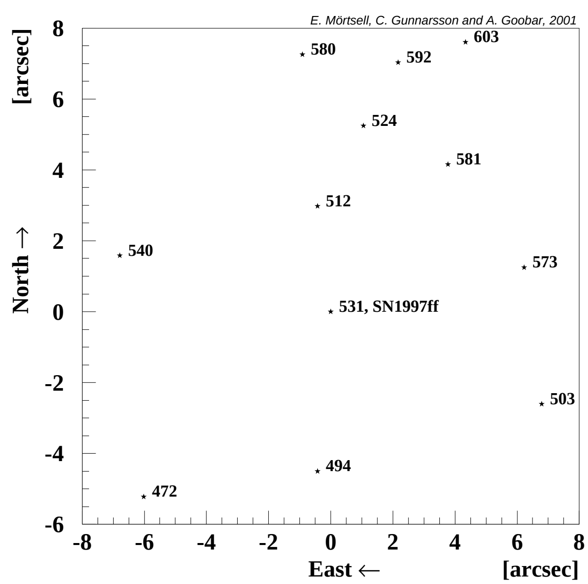

FIG. 1. The relative positions of galaxies lying closer than 10 arcseconds from SN1997ff in the HDF-N. The corresponding redshifts, masses and velocity dispersions are tabulated in Table I.

We model the matter distribution of the galaxies as truncated isothermal spheres with density profiles

$$\rho(r) = \frac{v^2}{2\pi}\frac{1}{r^2}, \tag{1}$$

where the velocity dispersions, v, are given by the Faber-Jackson relation

$$\frac{v}{v_*} = \left(\frac{L}{L_*}\right)^{0.25} = 10^{0.1(M-M_*)}. \tag{2}$$

Here, M is the absolute magnitude of the galaxy as measured in the b_J magnitude system and L is the luminosity. The star indicates typical galaxy values on v, L and M (and the mass, m, below). We calculate M by performing cross-filter K-corrections (assuming early-type galaxy spectra) on the observed magnitudes in the r and i bands (ST magnitude system) into rest-frame b_J.

To estimate the masses of the lensing galaxies, we combine the observed luminosities with the mass-to-luminosity ratio [6]

$$\frac{m}{m_*} = \left(\frac{L}{L_*}\right)^{1.25} = 10^{0.5(M_*-M)}, \tag{3}$$

valid for early-type galaxies lying in the fundamental plane. We can derive an expression for the mass normalization, m_*, by assuming that the luminosities of the galaxies are accurately described by the Schechter luminosity function over the entire luminosity range, see [7]

$$m_* \sim 1.3 \cdot 10^{14}\,\Omega_{\rm gal}\left(\frac{0.7}{h}\right)\left(\frac{10^{-2}h^3}{n_*\,{\rm Mpc}^3}\right)m_{\rm sun}, \tag{4}$$

where $\Omega_{\rm gal}$ is the mass density in galaxies and n_* is the number density of galaxies. From the velocity dispersion and mass of the galaxies, we can compute the cut-off radii for the projected mass (see below) of the halos as

$$d = \frac{m}{\pi v^2}. \tag{5}$$

The galaxies are placed according to Fig. 1 at respective redshifts, see Table I. The magnification and deflection of the light from SN1997ff are calculated by using the multiple lens-plane method [8, Ch. 9]. The mass of each of the lensing galaxies is projected onto a plane at the galaxy redshift. The surface mass density obtained is, after being appropriately scaled, called the convergence. For a circularly symmetric lens, the convergence along with the total mass within the radius of impact of the ray on the lens completely characterizes the lensing effects. Next, the deflection angle and magnification in each plane is computed by tracing light-rays backwards from the observer to the source, thereby enabling us to determine the magnification and position of the ray. By using a grid of light rays, we are able also to determine the shape of an extended source in the absence of lensing, i.e., its intrinsic shape, see Sec. IV. In Figs. 2 and 3, SN1997ff is assumed to reside at exactly the host galaxy center coordinates.

Our calculations have been made using $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ and the filled beam approximation when calculating cosmological distances. A typical value of $v_* = 238$ km/s was obtained in Ref. [9] for this cosmology.

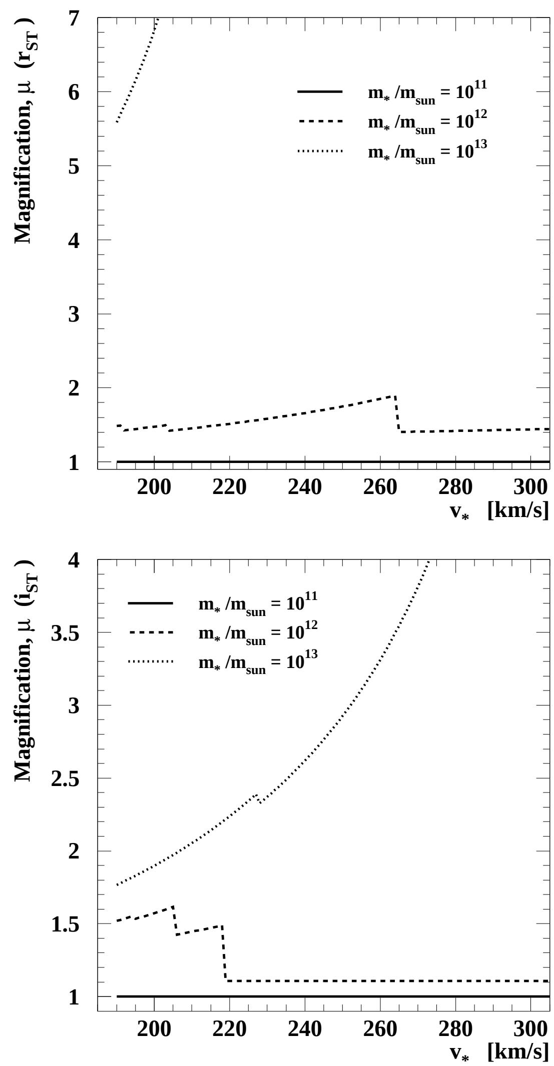

FIG. 2. The magnification, μ, as a function of the typical galaxy velocity dispersion, v_*, for three different values of the typical mass, m_*. In the upper panel, the velocity dispersion and masses of the galaxies are computed from the observed luminosities in the $r_{\rm ST}$-band, in the lower panel from the $i_{\rm ST}$-band.

III. RESULTS

In Fig. 2, the magnification of SN1997ff is given as a function of the normalization of the velocity dispersion of the galaxies for three different values of the mass normalization, m_*. The velocity dispersions are calculated from luminosities in the $r_{\rm ST}$-band (upper panel) and $i_{\rm ST}$-band (lower panel). Note that the normalization of the velocity dispersion sets the concentration of the galaxies [see Eq. (1)] whereas the mass normalization sets the total mass of the galaxies. For a circularly symmetric lens, the magnification is determined by the mass within the radius defined by the impact parameter of the light-ray and the convergence at this radius, see Sec. II. Since the size of the galaxies is inversely proportional to the velocity dispersion squared, a higher velocity dispersion can mean a lower magnification since halos get smaller which may cause light-rays to pass outside halos, thus losing the convergence component in the magnification. It is this effect that causes the drops in the magnification curves in Fig. 2.

In Fig. 3, the magnification is given as a function of the normalization of the mass of the galaxies, m_*, calculated from luminosities in the $r_{\rm ST}$-band (upper panel) and $i_{\rm ST}$-band (lower panel). Note that the magnification grows discontinously with m_*, an effect similar to the drops in the magnification curves in Fig. 2. In this case, it is due to the fact that larger masses gives larger halos, and thus it is possible to suddenly gain the convergence component of the magnification when the mass and accordingly the halo size are increased. Of course, these effects are unphysical in the sense that they are very sensitive to the specific modeling of the halos, in this case the steepness of the density profile and the cut-off radii. It is also an indication that lensing effects are very model dependent, and thus very detailed, individual modeling of the lensing galaxies is necessary to make robust predictions of the magnification.

From our ray-tracing calculations, we find that in order to have multiple imaging of SN1997ff, we need to have large values of v_* and m_*. Also, since there is no visible secondary image of the host galaxy, if multiply imaged, the secondary image has to be very weak. We will therefore not treat the case of multiple imaging of SN1997ff in this paper.

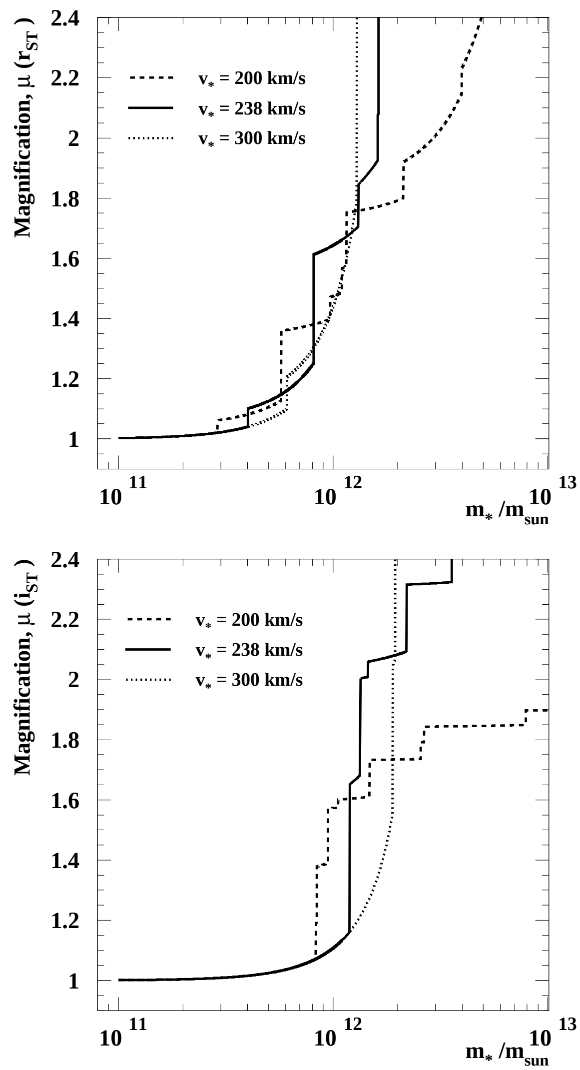

FIG. 3. The magnification, μ, as a function of the mass normalization, m_*, for three different values of the typical velocity dispersion, v_*. In the upper panel, the velocity dispersion and masses of the galaxies are computed from the observed luminosities in the $r_{\rm ST}$-band, in the lower panel from the $i_{\rm ST}$-band.

IV. CLUES FROM HOST GALAXY

The appearance of the host galaxy might offer some clues to the magnitude of the lensing effect. The reason is that one expects an extended source to be tangentially extended in the case of lensing. For an isothermal lens and a magnification factor μ, the image will be tangentially stretched by a factor μ [1]. Since the host galaxy looks very close to round (the minor to major axis ratio b/a is 0.85), if highly magnified, the intrinsic shape of the galaxy will have to be very elliptical and oriented in such a way as to counteract the tangential distortion due to lensing effects. This effect has been used by Riess et al. [1] to argue that, assuming random intrinsic orientation and an intrinsic ellipticity distribution according to [10], the probability to observe such a small ellipticity in the host galaxy is $\sim 14\%$ for a magnification of 0.4 mag and $\sim 3\%$ for a magnification of 0.8 mag. These probabilities were calculated for lensing from galaxy No. 512 only.

In Fig. 4, we have plotted the observed shape and orientation as well as the intrinsic shape and orientation of the host galaxy for four different cases, including lensing effects from all nearby galaxies in the field. The central point where we put the SN is indicated in a different shade. In the upper panel, masses and velocity dispersions are calculated from luminosities in the $r_{\rm ST}$-band, in the lower panel from the $i_{\rm ST}$-band. We see that the intrinsic ellipticity of the host galaxy in fact only has a rather mild dependence on the magnification, μ, in contrast to the analytical result for a single isothermal lens. As an example, in the lower right panel of Fig. 4, we have a magnification factor of $\mu = 2.1$ (corresponding to a magnification of 0.8 mag) with an intrinsic axis ratio of $b/a = 0.47$ (corresponding to a E5 galaxy). From Fig. 2 in [10] it is clear that an axis ratio of $b/a = 0.47$ is only a factor ~ 1.5 mor rare than the observed ratio of $b/a = 0.85$. Thus, comparing the results in Fig. 4 with the results of [1] it is evident, that when including the effects from all galaxies in the field, the constraints on the intrinsic ellipticity of the host galaxy is considerably relaxed. Thus, we conclude that it is — unfortunately — hard to constrain the magnification of SN1997ff from the apparent ellipticity of the host galaxy.

V. SUMMARY

We have investigated the effects of gravitational lensing on the magnification of SN1997ff and the appearance of the host galaxy. Our results show that a large range of magnifications is possible for reasonable values of the galaxy masses and velocity dispersions. The value of the magnification is very sensitive to details in the modeling of the matter distribution in the lensing galaxies. Furthermore, we have found that the apparent (lack of) ellipticity of the host galaxy does not put any strong constraints on the magnitude of the magnification effect.

Thus we conclude, that in order to use the apparent magnitude of a single high redshift SN to infer the values of $\Omega_{\rm M}$ and Ω_Λ, or even to place meaningful limits on the possible dimming of Type Ia SNe by intergalactic grey dust or luminosity evolution, very careful modeling of the galaxies along the line-of-sight is needed in order to control the systematic effects from lensing.

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TABLE I. Data for galaxies in the HDF-N, closer than 10 arcseconds to the line-of-sight to SN1997ff. Redshifts in boldface are photometric redshifts used in cases where spectroscopic redshifts are not available.

No.	z	$m/m_*(r_{\rm ST})$	$m/m_*(i_{\rm ST})$	$v/v_*(r_{\rm ST})$	$v/v_*(i_{\rm ST})$
472	**1.107**	2.863	0.700	1.234	0.931
494	0.873	2.481	0.670	1.199	0.923
503	0.847	0.675	3.197	0.924	1.262
512	0.555	0.986	0.520	0.997	0.877
524	0.557	0.802	1.106	0.957	1.020
540	**0.776**	0.021	$8.1 \cdot 10^{-3}$	0.463	0.382
573	**0.468**	$5.0 \cdot 10^{-4}$	$5.3 \cdot 10^{-4}$	0.218	0.221
580	**1.500**	19.378	2.185	1.809	1.169
581	**1.225**	1.480	0.270	1.082	0.770
592	**0.776**	0.194	0.062	0.721	0.573
603	**0.363**	$1.4 \cdot 10^{-4}$	$4.7 \cdot 10^{-4}$	0.170	0.216

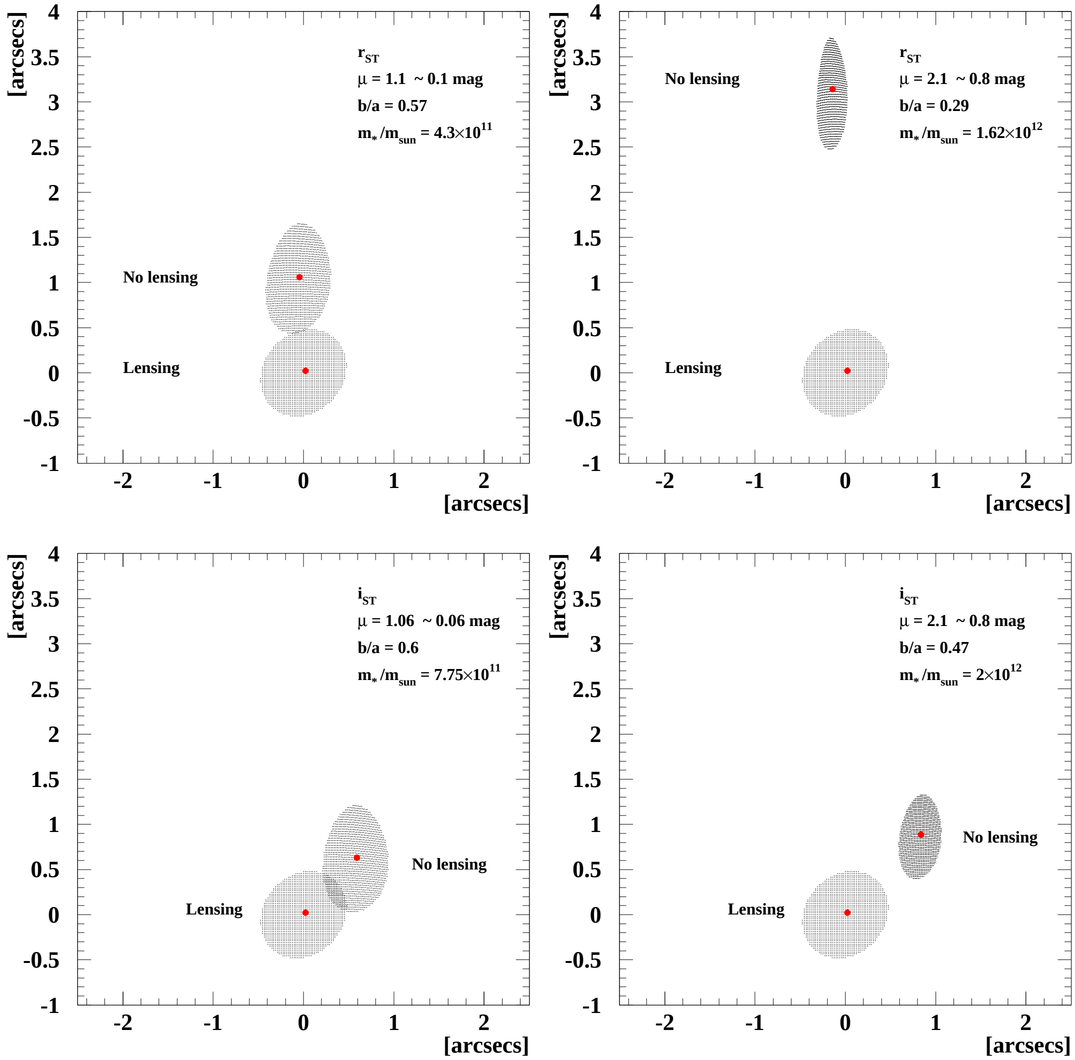

FIG. 4. The apparent (Lensing) and intrinsic (No lensing) shape of the host galaxy No. 531, for different levels of magnification. The normalization of the velocity dispersion used is $v_* = 238$ km/s. In the upper panel, masses and velocity dispersions are calculated from luminosities in the $r_{\rm ST}$-band, in the lower panel from the $i_{\rm ST}$-band. The axis ratio of the image b/a is 0.85.